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A NEW MEASURE OF TELEVISION DISPLAY QUALITY RELATABLE TO OBSERVER PERFORMANCE

AEROSPACE MEDICAL RESEARCH LABORATORY

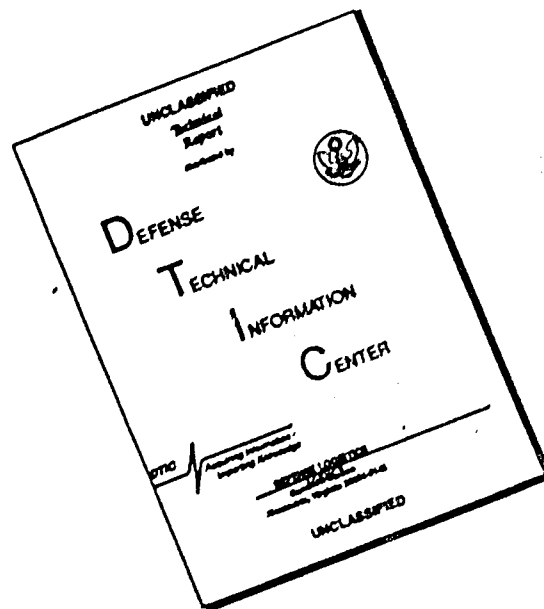
AUGUST 1976

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TECHNICAL REVIEW AND APPROVAL

AMRL-TR-76-73

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 80-33.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



CHARLES BATES, JR.
Chief
Human Engineering Division
Aerospace Medical Research Laboratory

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes a new, direct measurement method of determining the imaging quality of cathode-ray tube (CRT), line scan displays. This measurement was specifically developed as a more critical and realistic indicator of display quality. The measurement consists of recording the modulation contrast available on the display as a function of spatial frequency. An electronic sine wave generator produces a sine wave intensity pattern on the face of a CRT		

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ABSTRACT (cont'd)

display. The display luminance distribution is scanned using a telephotometer or microphotometer depending on the size of the display.

The modulation contrast of the display is obtained from the photometer scan for several spatial frequencies. The resulting graph showing modulation versus frequency is defined as the Sine Wave Response (SWR) Curve of the display.

Since human vision is not linearly related to modulation, it is desirable to transform the modulation axis to another parameter which is linearly related to vision.

This can theoretically be accomplished by transforming the modulation contrast to $\sqrt{2}$ incremented Gray Shades. The resulting Gray Shade Response (GSR) indicates how many gray shades are visible as a function of spatial frequency.

A new single display quality metric is defined using the GSR curve of a display. The measure is derived from the Modulation Transfer Function Area (MTFA) concept and is defined as the area between the visual threshold curve and the GSR. This area is referred to as the Gray-Shade Frequency Product or GFP.

A brief study was performed to determine the correlation of GFP with performance in a target recognition task. The results for three display conditions indicate that the GFP is at least as good a measure of display quality as MTFA.

PREFACE

The work described in this report was accomplished under Project 7184, Task 11, Work Unit 01: Image/Display Quantification. The purpose of this work unit is to develop a suitable measurement methodology for display devices and to relate this measure to observe performance. Partial funding for this work was obtained from DAIS (Digital Avionics Information System, Project 2050, Work Unit 2050 0701: Quantification of Imaging Display Performance).

The authors wish to extend their thanks to those who assisted in obtaining the data presented in this report. We especially wish to thank Mr. Mike Poole who was responsible for making the display measurements and Mr. Alan Pinkus and Mr. John Burgess who were responsible for reducing the raw data.

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INTRODUCTION

A major problem facing today's Armed Forces is the ability to convert real world requirements into precise and relevant equipment specifications. An example of this problem is the situation involving raster-scanning cathode-ray tube displays (television displays).

Phenomenal advances in electronic display technology have not yet changed the primacy of the cathode-ray tube (CRT) in the area of video information displays (see Table 1). Yet, a comprehensive measure of television display image quality which relates to human operator performance has not evolved, even though numerous studies have investigated various facets of this measurement problem during the past thirty years.

This situation is directly relatable to the lack of standardization in display performance metrics. Currently, no universally acceptable technique exists for analyzing television display system quality. Each manufacturer establishes its own test, measurement, and evaluation procedures.

The lack of standardization in measurement techniques makes it virtually impossible to establish comprehensive performance specifications. Presumably, television display manufacturers publish specifications so that prospective buyers can evaluate these data before selecting a particular unit for their needs. But, it is difficult to find a common denominator of CRT performance to permit a comparison of units built by various manufacturers on the basis of performance. Some manufacturers give rather complete lists of video amplifier performance specifications and imply the transfer function of the CRT is unity. Most manufacturers give incomplete or misleading data concerning the quality of their CRT displays.

This report introduces a new and potentially powerful technique for analyzing television display quality and compares it with other techniques currently being used. This new technique is based on empirical psychophysical data obtained from human visual performance tasks and on an extension of Modulation Transfer Function (MTF) theory. Using this improved metric, it eventually should be possible to measure the resultant quality of both the CRT and its associated driving electronics in such a way as to predict observer performance in target detection, recognition and identification tasks.

The theory, equipment, and procedures involved in the display quality measurements, in addition to the problems encountered in making these measurements, are discussed in detail.

TABLE 1. ELECTRONIC DISPLAY TECHNOLOGY PERSPECTIVE*

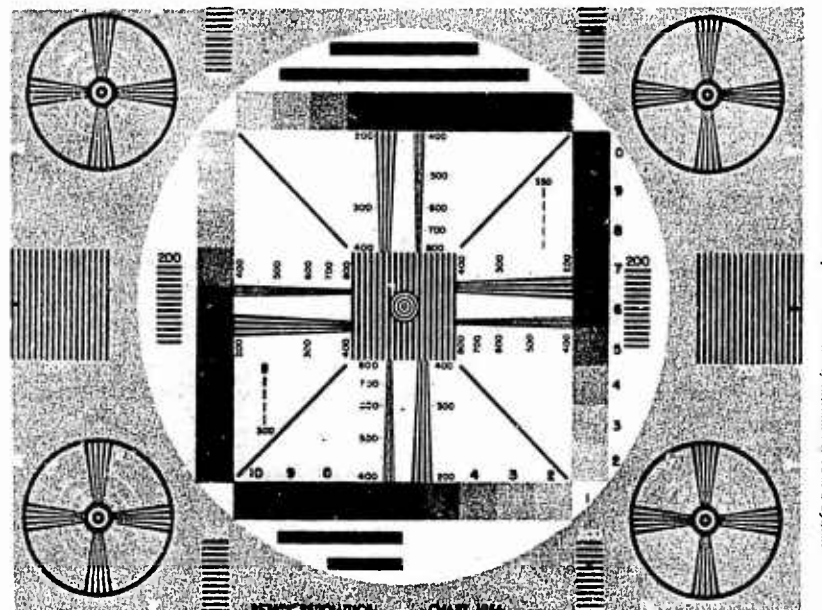
Display Application	Available	In R&D
Discretes	Electromechanical Incandescent Light-Emit. Diode	Liquid Crystal
Alphanumeric	Cathode-Ray Tube Electromechanical Incandescent Light-Emit. Diode Liquid Crystal Plasma	Chemoluminescent Electrochromics Electroluminescent Electrophoretics
Vectographic	Cathode-Ray Tube Plasma Panel	Electroluminescent Light-Emit. Diode Liquid Crystal
Video	Cathode-Ray Tube	Electroluminescent Laser Liquid Crystal Plasma Panel

*From Reference 18

BACKGROUND

The resolution of optical elements has been measured for years by means of two-dimensional bar patterns with various spacings and angular arrangements. The optical element under investigation forms an image of the bar pattern, and the observer subjectively determines the limiting resolution from the smallest set of bars he can perceive. With this type of test it is possible to determine only a subjective maximum "resolution." There is too much variability in this method of measurement for it to be used as a basis for setting specifications. As the observer changes so does the subjective maximum resolution value.

The U.S. Air Force, National Bureau of Standards (NBS), Electronic Industries Association (EIA), and other groups interested in finding a solution to this measurement problem developed several different types of resolution charts in an effort to establish a more reliable test. The EIA Resolution Chart (formerly RETMA Chart, 1956) is currently the most popular chart for subjective evaluation of television system performance (see Figure 1).



From Reference 13

Figure 1. EIA Resolution Chart (Formerly RETMA Chart, 1956)

While the controversy about the best type of resolution chart continued, Otto H. Shade (Reference 16) introduced a new approach to optical system evaluation. Shade was working in the area of communications and was intent on improving the response capabilities of television systems. Shade is recognized as the individual responsible for the method of electro-optical

(E-O) system analysis called "Sine Wave Testing." This method has led to what we now call "Modulation Transfer Function" analysis.

Shade wanted to optimize the complete TV system from camera to display. From electrical systems analysis he knew he could study the response of electrical elements by either of two methods: transient analysis of a square pulse input, or amplitude and phase analysis of a variable frequency sine wave input. The transient analysis is more difficult to use experimentally. Shade reasoned he should be able to analyze optical elements with techniques similar to those he had applied to electronic elements. The variations in intensity with angle as seen by a lens corresponds to the variations in voltage with temporal frequency. The variation in intensity in the former case is also a function of frequency--spatial frequency.

The concept of spatial frequency is fundamental to the understanding of MTF analysis. Spatial frequencies, either in a test object or in the image of the object formed by the system, are expressed in units of cycles per unit length. Spatial frequencies are thus analogous to the familiar temporal frequencies expressed in units of cycles per unit time.

Shade and his contemporaries investigated the transfer function of the entire E-O system; from sensor through CRT. The measurement techniques developed in this paper apply only to the television display (i.e., the CRT and its driving electronics). The need exists for both types of performance measures. When purchasing a packaged E-O system, a judgment of the quality of a system is usually made on the basis of the system transfer function--its capability of transferring spatial information through the sensor to the display. When assembling an E-O system from components or replacing components in a packaged system, the response of the individual components must be known since the selection of each component impacts the resultant system performance. A poor choice of a single component can have a devastating effect on the overall system performance since the E-O system response is obtained by a point-by-point multiplication of the component transfer functions (see Figure 2). By the same rationale, using a more expensive component with much better performance than the other components may not significantly improve system performance.

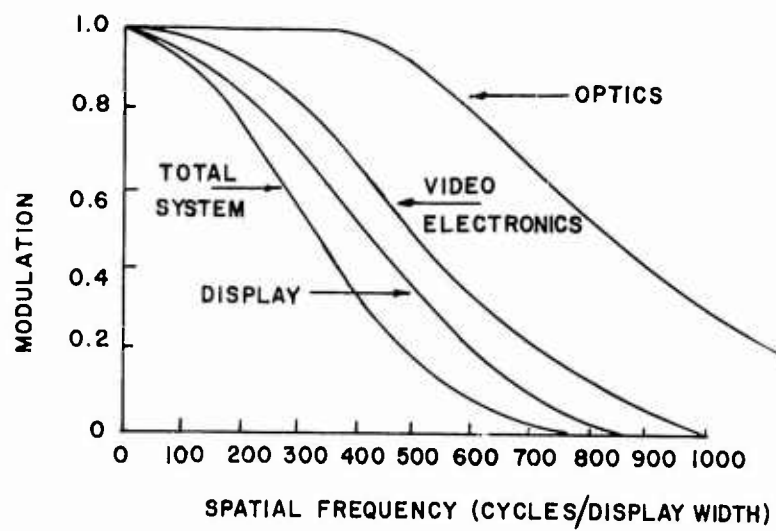


Figure 2. Resultant System Response Calculated from Responses of Components

CRT DISPLAY MEASUREMENT: THEORY

The Modulation Transfer Function (MTF)

In the past several years the MTF measure of display quality has received considerable attention. The MTF has been used as an indicator of the quality of film and photographic systems, of optical systems and lenses and more recently of CRT displays. Theoretically the MTF of a system indicates the percent modulation the system will pass as a function of spatial frequency for a sine wave signal.

Since any signal (or picture) theoretically can be resolved into a set of component sine waves, it is possible to predict how the signal (picture) will appear after passing through a system with a known MTF. Therefore, if the MTF of a system is known, the signal (picture) degradation caused by that system can be calculated. However, the system must be linear and continuous before MTF techniques can be applied. Unfortunately, CRT displays are nonlinear devices, so care must be taken when applying MTF analysis to them.

There are several ways to obtain the MTF of a CRT display. Most of these methods require mathematical manipulation of empirically measured signals and assume linearity of the CRT display.

Mathematically, the MTF of a system is defined as the Fourier transform of the point spread function of the system. The point spread function is the resultant output signal from a system for a point or "narrow" impulse input signal. Rigorous treatment requires the input to be of zero width and infinite height; practically, the "spike" needs to be "much narrower" than the spread caused by the system being tested. For CRT displays, the point spread function is typically obtained by measuring the spot profile produced on the face of the CRT by the scanning electron beam. This "spread function" is then used to obtain the MTF by applying the Fourier transform theory. Another approach is to assume the spot profile is a Gaussian distribution (equation 1) and calculate the MTF from equation 2. A Gaussian distribution is used because the Fourier transform of a Gaussian distribution is easily obtained in analytic form, thus eliminating the necessity of using numerical Fourier transform techniques and a computer. (CRT spot profiles are typically near Gaussian.) Equation 2 is the Fourier transform of equation 1.

Gaussian luminance distribution of CRT spot

$$B(x) = K e^{-1/2(x/\sigma)^2} \quad (1)$$

where

B = luminance distribution

K = constant

x = spatial parameter (length)

σ = standard deviation of the Gaussian distribution

Taking the Fourier transform of equation 1 yields the MTF

$$\text{MTF}(f) = e^{-2(\pi\sigma f)^2} \quad (2)$$

where

f = spatial frequency

σ = standard deviation of Gaussian distribution

MTF(f) = fractional modulation

Figure 3 shows a typical MTF generated by this method.

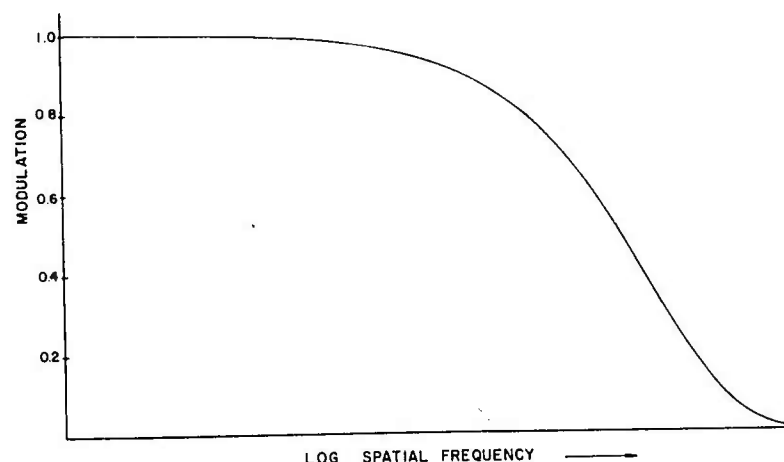


Figure 3. Typical MTF Obtained from Calculations Based on Assuming a Gaussian Distribution Spot Profile as a Point Spread Function

Other methods of obtaining the MTF of a CRT display require Fourier analysis of square wave, line or edge patterns. In each case the MTF must subsequently be calculated, assuming linearity of the display.

The direct method of obtaining the display MTF is to measure the modulation transfer of the display for sine wave signals of various

frequencies. The problem with applying this approach to CRT displays is that the input signal is electronic (measured in volts) and the output signal is photometric (measured in footlamberts). Thus, the output to input ratio (percent of modulation transfer) is not clearly defined. Typically, this problem is circumvented by using a normalization procedure, the results of which can be misleading.

The Sine Wave Response (SWR)

The SWR measurement was devised to avoid the problems inherent in calculating the MTF by using the various methods described. The SWR relates the maximum modulation contrast capability of the display to spatial frequency, measured directly, frequency by frequency. This differs from the MTF in two important respects: (1) it does not assume linearity of the CRT display, and (2) it is not a normalized function. Later in this report the importance of these two characteristics will become more apparent.

Figure 4 shows the electronically generated sine wave video signal used to measure the SWR. This signal is set up to duplicate the voltage level characteristics of the TV camera or sensor with which the display under test will be used.

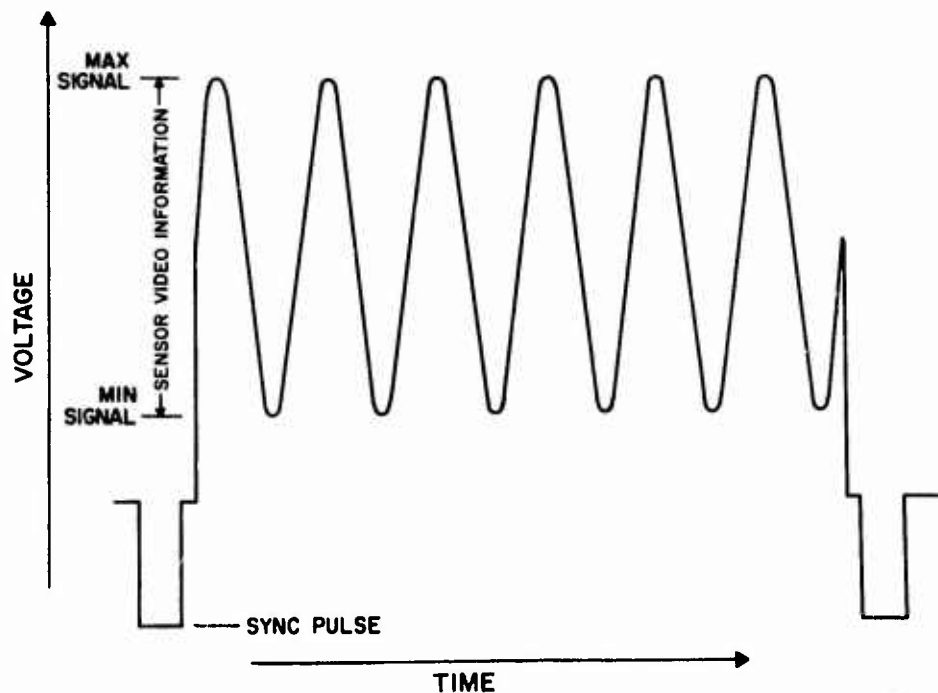


Figure 4. Electronically Generated Video Sine Wave

With this signal as the input to the display, the luminance distribution across the face of the display is measured by scanning with a photometer.

The modulation contrast is found using equation 3.

$$M_C = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}} \quad (3)$$

where

M_C = modulation contrast

B_{\max} = peak luminance level

B_{\min} = minimum luminance level

This is repeated for several spatial frequencies until the entire SWR is obtained. Figure 5 shows a typical SWR for a display.

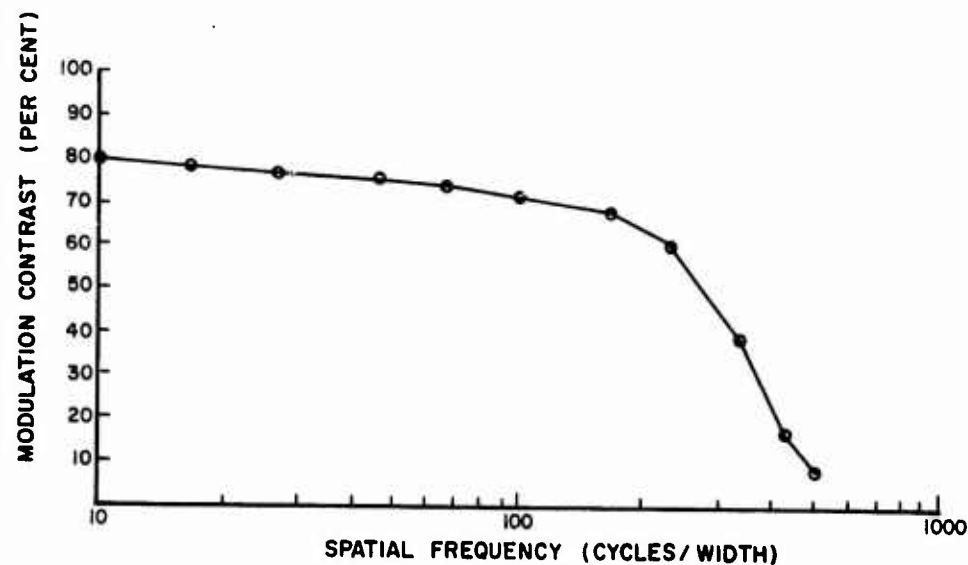


Figure 5. Typical Sine Wave Response (SWR) Curve for a Miniature CRT Display

The Video Transfer Function (VTF)

Since the brightness and contrast controls of a television display have enormous effects on the SWR measurement, it is necessary to devise a reliable method for adjusting these controls. The method described herein maximizes the dynamic range (contrast) of a display without causing loss of video due to black level clipping.

The adjustment is accomplished as follows: A video signal similar to the one shown in Figure 6 is generated and displayed on the CRT face. The high and low video pulses are set at the peak and valley voltages, respectively, of the video sine wave shown in Figure 3. This also corresponds to the maximum and minimum signal voltages from the E-O sensor.

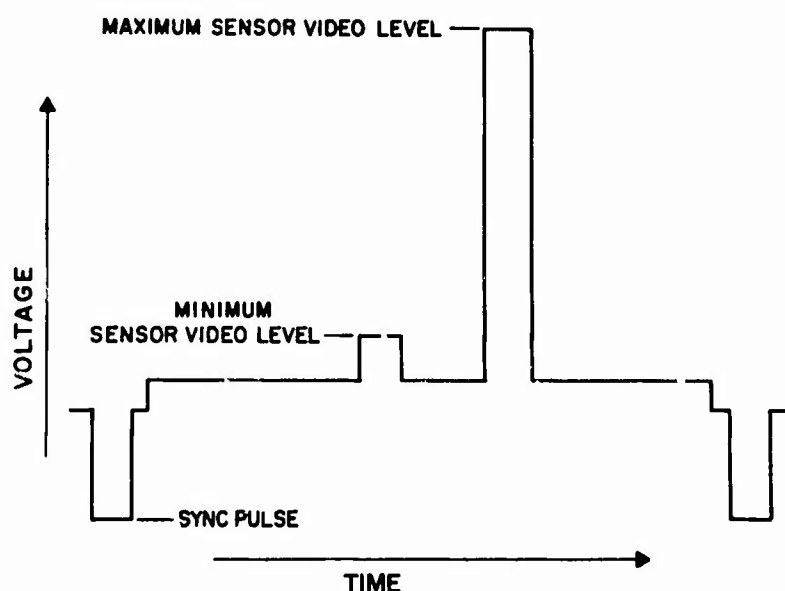


Figure 6. Electronically Generated Signal Used to Set Display Brightness and Contrast Controls

The brightness and contrast controls are iteratively adjusted to obtain a luminance of B_{\max} for the high intensity bar and two percent of B_{\max} for the low intensity bar. The value of B_{\max} is chosen to be compatible with the capabilities of the display being tested and the applications for which it is intended. The two percent of B_{\max} value for the low luminance shade was chosen to ensure high modulation contrast (96%) and to make certain that video information loss due to black level clipping was eliminated. (It should be noted that this particular video signal can only be used with displays which clamp to black level or the bottom of the sync pulse to obtain

DC restoration. Displays using an average signal level for DC restoration require the use of a low frequency square wave with this adjustment procedure, i.e., a series of bright and dim gray shades. This ensures that the video test signal has about the same average value as a video signal from an E-O sensor.)

After the display controls have been adjusted, the luminance of the low voltage bar is measured as a function of its signal voltage as it is raised to the level of the high voltage bar. Figure 7 shows the resulting curve. This is the Video Transfer Function of the display for a low spatial frequency signal.

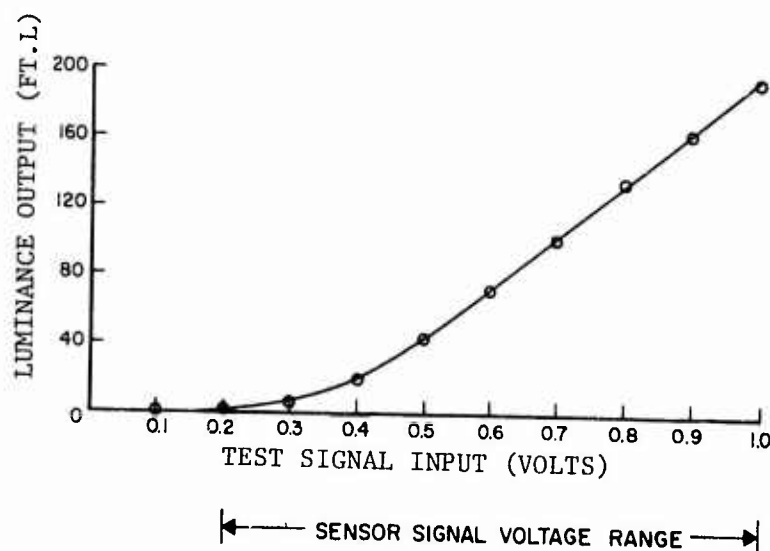


Figure 7. Typical Video Transfer Function (VTF)

The VTF yields useful information concerning the operating point of the display. From the VTF it is possible to determine if the display has been adjusted so as to cause black level clipping of video information at low frequency levels. It is also possible to determine how linearly the display operates and to what extent, if any, the display incorporates gamma correction circuitry.

CRT DISPLAY MEASUREMENT TECHNIQUES: APPLICATION

Measuring the VTF and the SWR of a CRT Display

As indicated in the previous discussion, the first step in obtaining the VTF and SWR curves is to adjust the brightness and contrast controls of the display being tested. The test signal used to adjust the brightness and contrast controls is shown in Figure 8.

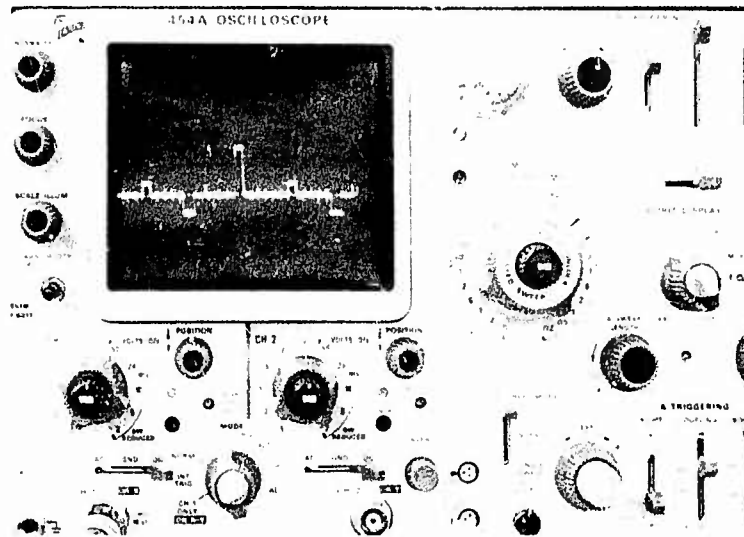


Figure 8. Two Pulse Gray Shade Test Signal as Seen on the Oscilloscope

This signal produces a pattern on the display similar to that shown in Figure 9.

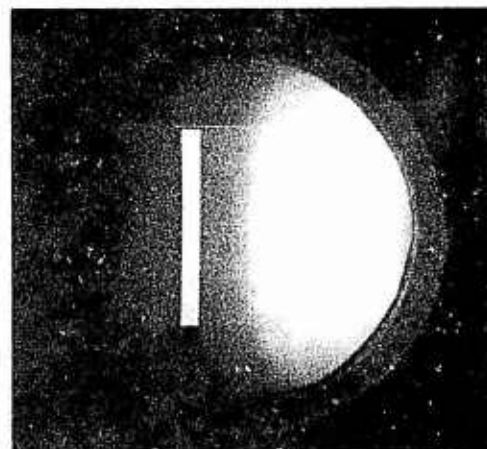


Figure 9. Miniature CRT Display with Two Pulse Gray Shade Input

With this two gray shade pattern on the display, the brightness and contrast controls are iteratively adjusted to obtain the predetermined peak luminance on the bright bar and the predetermined minimum luminance on the dim bar. Once this is accomplished the VTF is obtained by focusing the photometer on the dim bar and adjusting the voltage pulse of the bar in 0.1 volt increments. At each voltage level the luminance is recorded. The luminance versus voltage is then graphed as the Video Transfer Function (see Figure 10). As a matter of interest, Figures 11 and 12 show the effect of the brightness control and contrast control, respectively, on the VTF of a display.

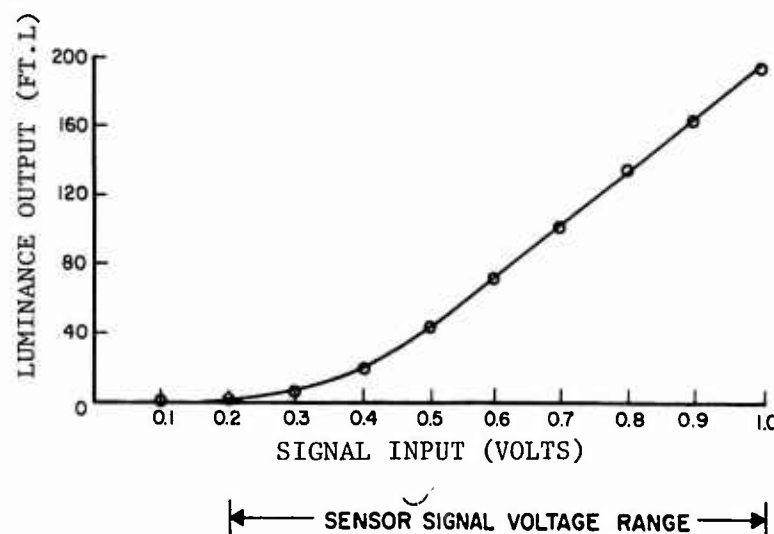


Figure 10. The Video Transfer Function (VTF)

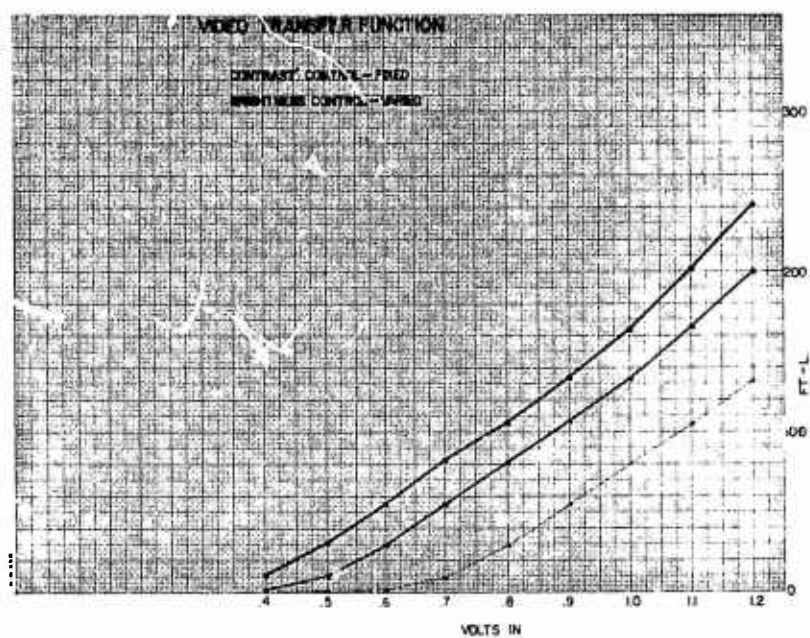


Figure 11. Effect of Three Different Brightness Control Settings on the VTF (with Constant Contrast Setting)

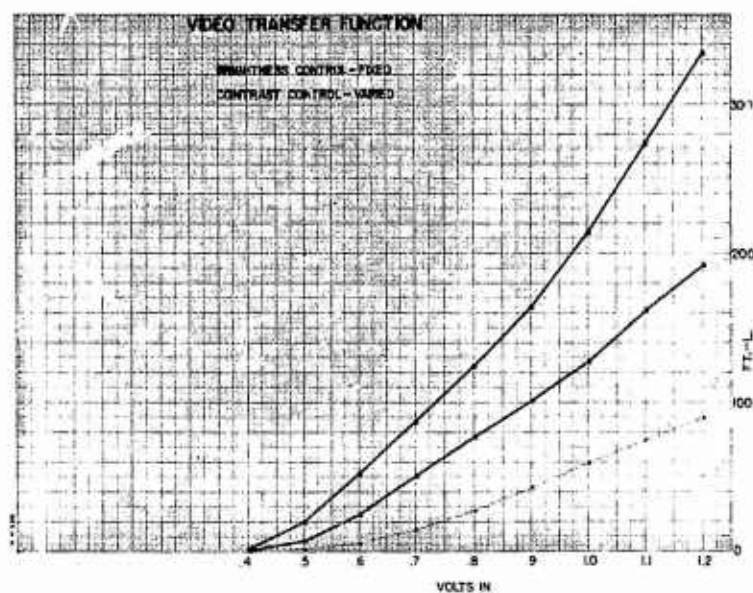


Figure 12. Effect of Three Different Contrast Control Settings on the VTF (with Constant Brightness Setting)

Once the brightness and contrast controls are properly adjusted, the Sine Wave Response (SWR) is measured.

The video test signal shown in Figure 13 is adjusted so that the peak and valley voltages of the sine wave correspond to the maximum and minimum video signals that the display would encounter in actual operation.

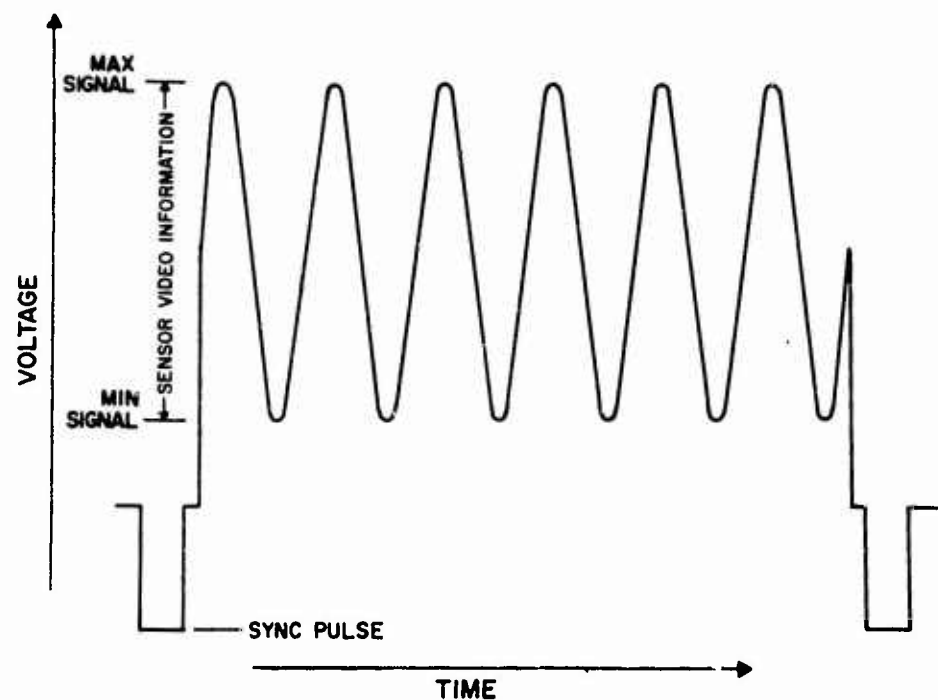


Figure 13. Electronically Generated Video Sine Wave

Figure 14 shows the CRT display as it appears with the video sine wave test signal input. The electronic focus control on the display is adjusted to obtain maximum modulation contrast of the test signal for a spatial

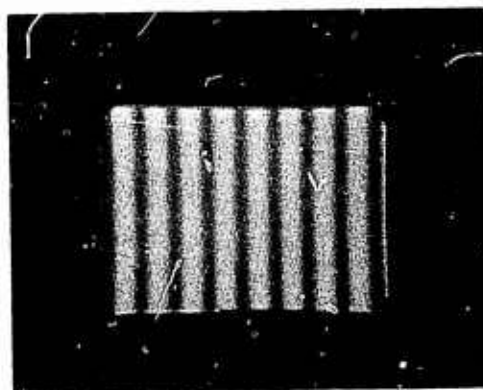


Figure 14. CRT Display with Sine Wave Input

frequency of approximately 200 cycles/display width. This ensures "sharpest" focus of the displayed image. The CRT face is then scanned with either a telephotometer (see Figure 15) or a microphotometer (Figure 16) depending on the size of the display. In either case, the scanning apparatus employs a vertical slit aperture with an effective width much smaller than the spot size of the display and with an effective height sufficient to measure the integrated average luminance across 6 to 10 scan lines.

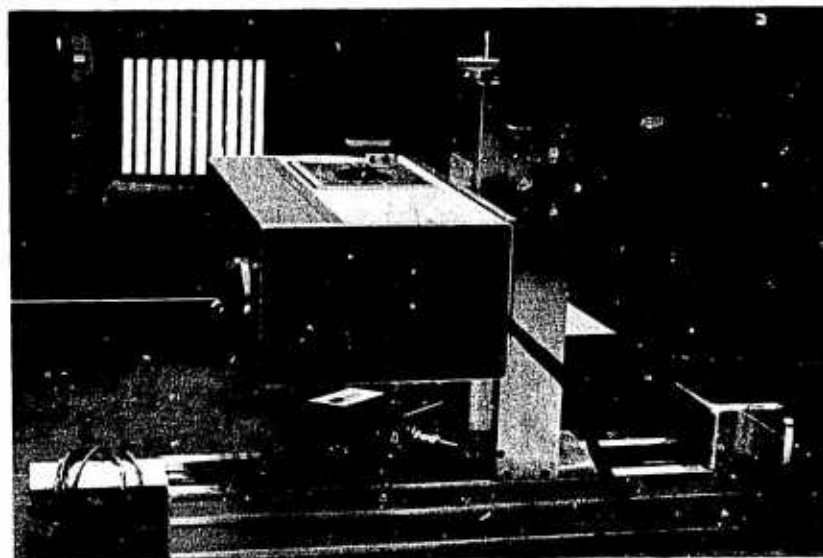


Figure 15. Telephotometer Used for Scanning Large Size Displays

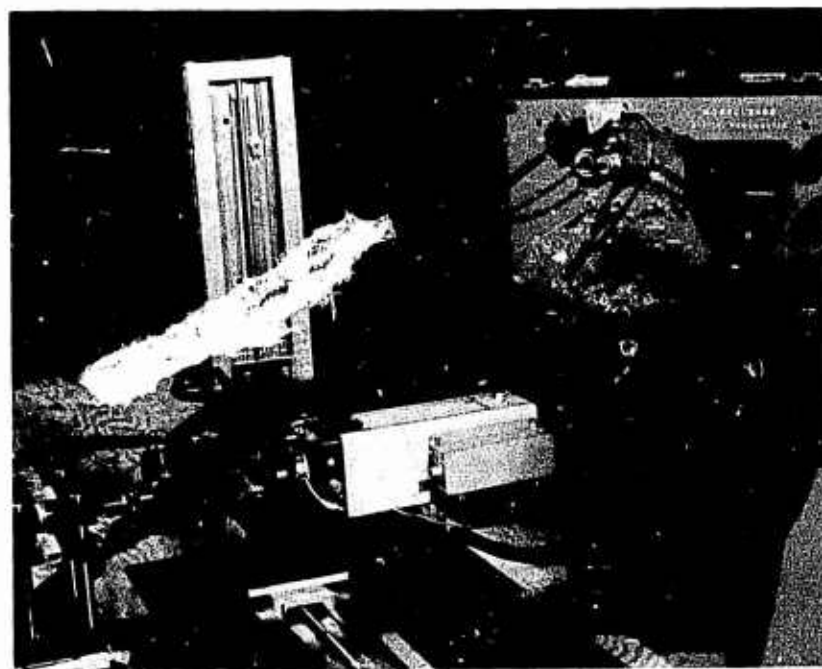


Figure 16. Microphotometer Used for Scanning Miniature Displays

Most of the work described in this report was accomplished with the microphotometer since most of the measurements were obtained from miniature CRTs used for helmet-mounted displays (see Bibliography). Figure 17 shows one of the miniature CRT displays tested.

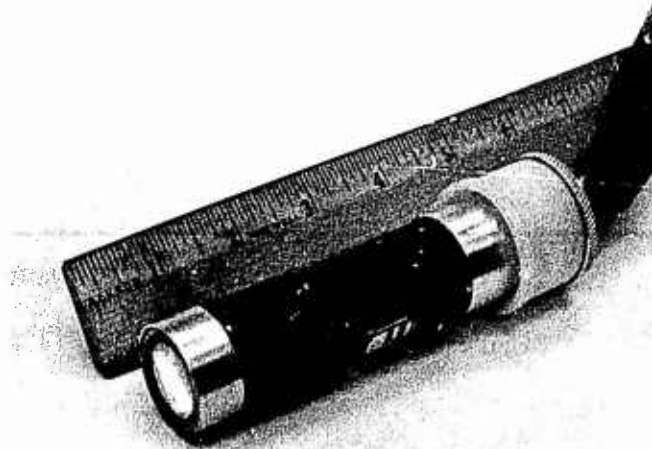


Figure 17. Miniature CRT Display

The resulting strip chart output from the photometer scan shows the luminance distribution across the display face. From these data the modulation contrast can be calculated using the equation:

$$M_c = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}}$$

This procedure is repeated for several spatial frequencies until the complete SWR curve is obtained. Figure 18 shows a resulting SWR for a representative CRT.

The first question that arose after establishing this procedure was: "How repeatable is it?" To answer this question, the VTF and SWR of a miniature CRT display were measured ten times over a period of three days. Before each measurement trial all controls were set to zero and then readjusted according to the previously described procedure. Figure 19 shows a graph summarizing the results. Based on this test it was apparent that the SWR was sufficiently reliable to be used as a measure of display quality and performance.

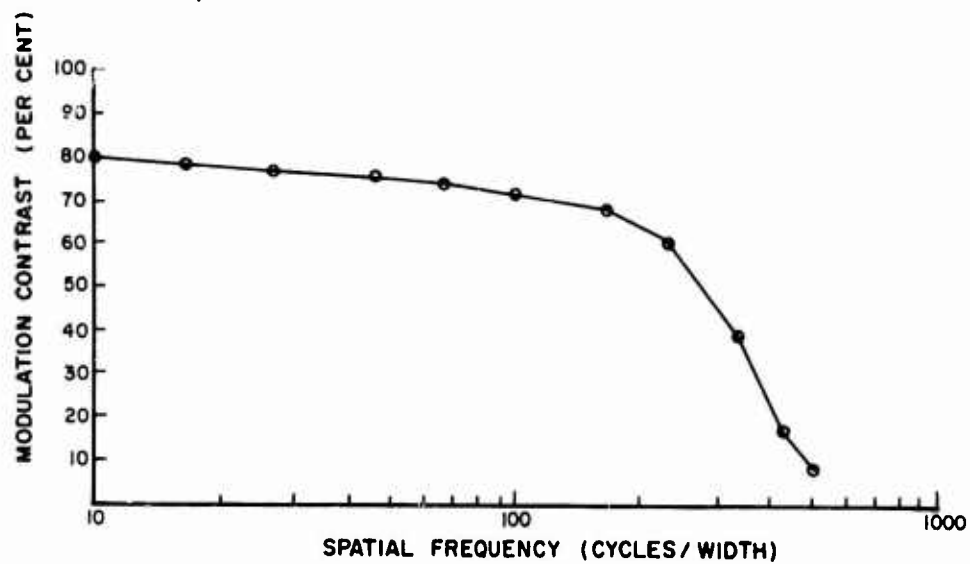


Figure 18. Sine Wave Response (SWR)

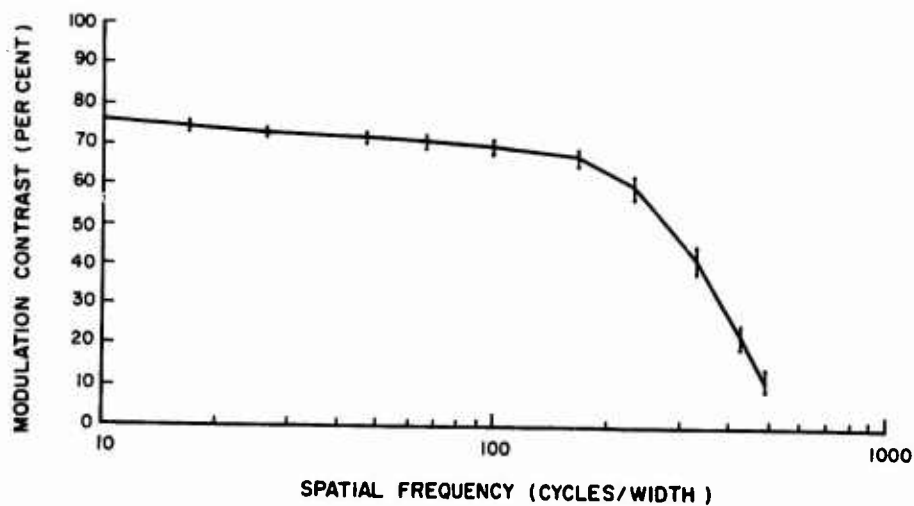
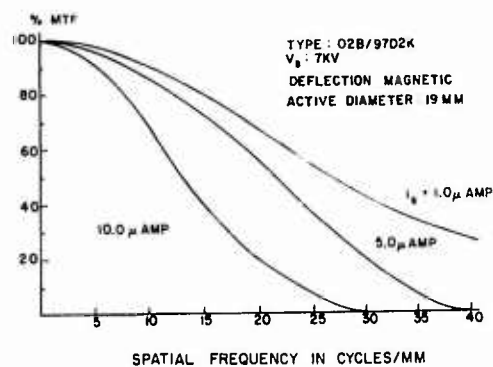


Figure 19. Repeatability Test. This graph shows the results of 10 repeated trials of measuring the SWR for a miniature CRT display. The vertical marks at each measurement point represent plus and minus one standard deviation of the modulation contrast obtained for each spatial frequency for the 10 trials.

Comparison of the MTF and the SWR

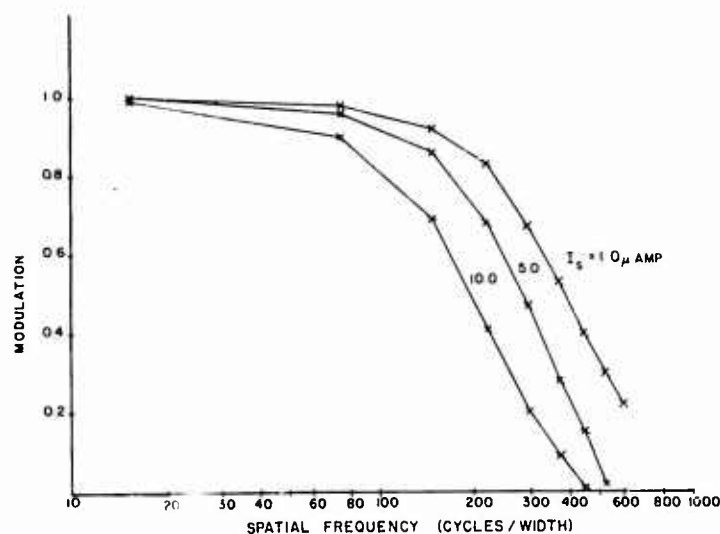
Since the SWR is obtained by making direct measurements of the modulation contrast available on the CRT, it is interesting to compare the SWR measure to the MTF. MTF data for the Ferranti miniature CRTs currently used in most helmet-mounted displays were published in reference 3. These MTF curves are shown in Figure 20.



From Reference 3

Figure 20. MTF of Ferranti Tube
(I_s = the screen current of the CRT)

These curves are replotted in Figure 21 in terms of cycles per width to make the format of the data compatible with SWR data and thus to facilitate direct comparison. This conversion was accomplished by multiplying the cycles/mm by 15.2 mm of active width of the raster. The 15.2 mm width represents the width of a 3:4 aspect ratio raster inscribed in a 19 mm active screen diameter. The raster format used for the helmet-mounted displays, and thus, for all of the described SWR measurements, is shown in Figure 22.



From Reference 3

Figure 21. MTF Data on Ferranti CRT (02B/97D2K) Replotted in Terms of Cycles/Width on Log Scale

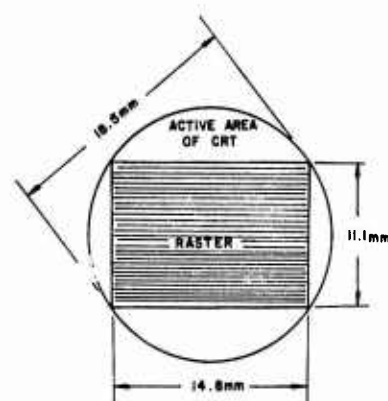


Figure 22. Scanned Area of Miniature Ferranti CRT (Note: active diameter of CRTs measured by authors is 18.5mm, slightly smaller than the 19 mm measured by Bedell)

A precise comparison of the MTF and the SWR is not possible since the operating point of the CRT for the MTF is given in terms of screen current, and the operating point for the SWR is given in terms of peak luminance and data relating these two variables is not immediately available. Therefore, the SWR for 50 footlamberts peak luminance and 600 footlamberts peak luminance are graphed in Figure 23 for qualitative comparison with the medium screen current (5.0 μ amp) and minimum screen current (1.0 μ amp) MTF as shown in Figure 21.

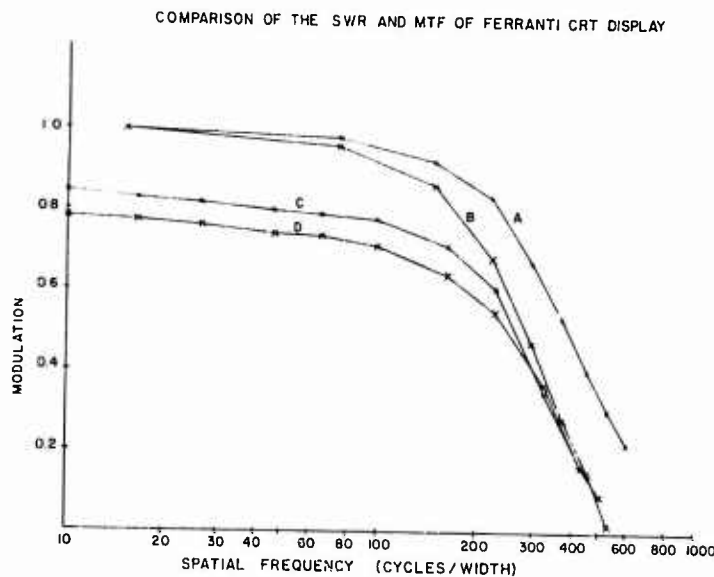


Figure 23. Comparison of SWR Curves and MTF Curve.
A) $I_s = 1.0 \mu\text{amp}$ MTF, B) $I_s = 5.0 \mu\text{amp}$ MTF,
C) 50 footlamberts peak luminance SWR, and
D) 600 footlamberts SWR.

Three of the curves show excellent agreement at the high spatial frequencies, indicating that the spot size for these three curves was approximately the same (all measured in the center of the same-type Ferranti CRT). However, the three curves differ for the lower and medium spatial frequencies. The SWR curves show that there is less modulation contrast available on the CRT face at lower spatial frequencies than the MTF measure indicates. This lower contrast is a real phenomenon and is apparent when viewing the display. The important point is that the MTF data are misleading in terms of modulation contrast for the lower and intermediate spatial frequencies. In fact, the two SWR curves indicate that as the luminance of the display is increased the light scatter problem is increased, thereby lowering the modulation contrast. It is apparent that the MTF data are relatively insensitive to this light scatter problem.

For a further comparison of the MTF and the SWR, the spot size of a Ferranti miniature CRT was measured and used to calculate the MTF by assuming the spot luminance distribution to be Gaussian. This was accomplished using the shrinking raster method of measuring spot size. The input to the CRT electronics was a "video window" test signal which provided a uniform luminance pattern on the face of the CRT. The vertical gain was then reduced until the raster could no longer be "seen." The scanning microphotometer was used to determine when the raster structure was no longer "visible." The resulting raster height divided by the number of active scan lines gave the spot width at the half intensity points (see Figure 24). From this width the value of σ for the Gaussian distribution equation was calculated.

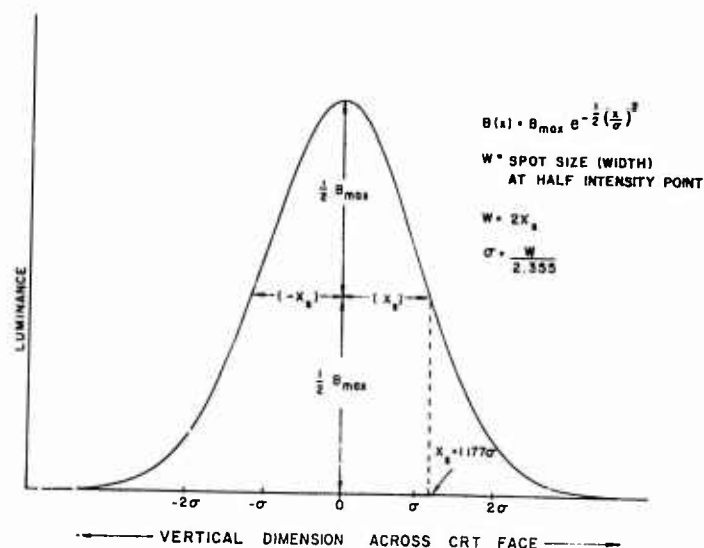


Figure 24. Gaussian Spot Luminance Distribution

$$B(X) = B_{max} e^{-1/2(X/\sigma)^2}$$

Referring to the equation of Figure 24:

$$B(0) = B_{max} e^{-(1/2)(0)^2} = B_{max}$$

The half intensity point is obtained by setting $B(X_S) = B_{max}/2$ where X_S = value of X for the half intensity point. Solving for the relation between σ and X_S :

$$\sigma = \frac{X_S}{\sqrt{(-2)\ln(1/2)}} = \frac{X_S}{1.177}$$

As shown in Figure 24, the spot width, W , is equal to two times X_S or:

$$\sigma = \frac{(1/2)W}{1.177} = \frac{W}{2.355} \quad (4)$$

The MTF calculated in this manner is compared in Figure 25 to the SWR for a peak luminance of 200 footlamberts. Again, there is good agreement for high spatial frequencies but poor agreement for the intermediate and lower spatial frequencies. The calculated MTF indicates a higher level of modulation than is present. It is apparent from these comparisons that the SWR direct measurement technique provides a more realistic measure of the CRT display's real imaging capability.

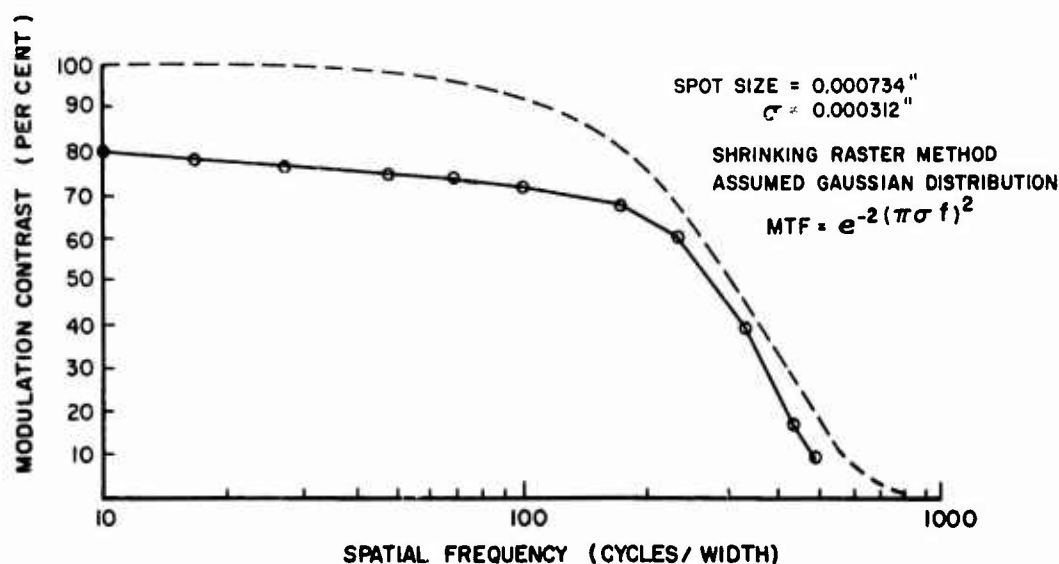


Figure 25. MTF Obtained from Spot Size Measurement Compared to SWR for a Peak Luminance of 200 Footlamberts

The Gray Shade Response (GSR)

The SWR provides a wealth of information concerning the capabilities of CRT displays. However, it does not necessarily permit direct quantification of image quality in terms of observer performance. It is desirable to obtain a quality measure which is directly relatable to operator performance in absolute as well as relative terms. The GSR is the first step in attaining this goal.

The SWR curve of a display describes the modulation contrast available on the display as a function of spatial frequency. The human visual system response, however, is nonlinearly related to modulation contrast. In order

to linearize this axis of the SWR, it is necessary to mathematically transform modulation contrast to some parameter which is linear with respect to the human visual system. It is possible to transform modulation contrast directly to gray shades using equation 5:

$$N = 1 + \frac{\log \left(\frac{1 + M}{1 - M} \right)}{\log \sqrt{2}} \quad (5)$$

where N = number of gray shades
M = sine wave modulation contrast on display

This equation assumes $\sqrt{2}$ gray shade steps as a convenient value. Figure 26 shows pictorially the transformation from modulation contrast to gray shades.

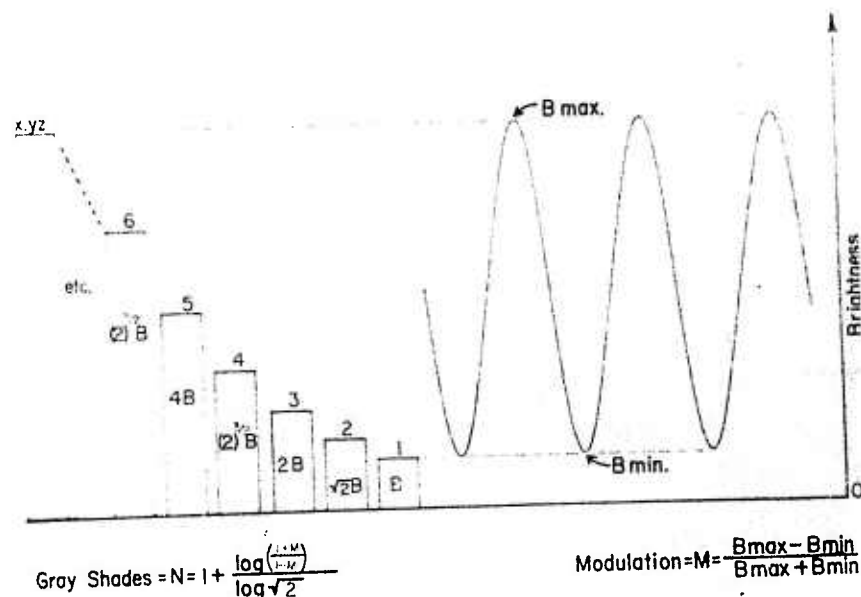


Figure 26. Conversion of Modulation Contrast to $\sqrt{2}$ Gray Shades

Using this transformation it is possible to change the SWR to a GSR curve, i.e., the maximum number of gray shades available on the display as a function of spatial frequency. Figure 27 shows an example of the GSR.

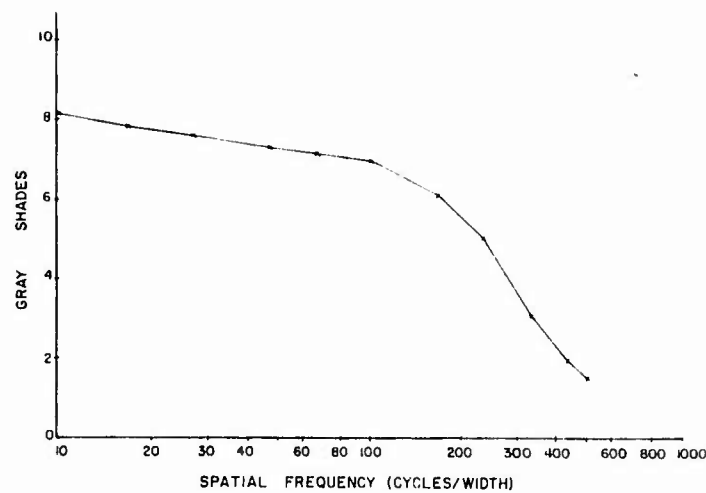


Figure 27. Typical Gray Shade Response

The GSR provides a great deal of information in a single graph. If the GSR is obtained for a display at several luminance levels, then the operating capability of that display is almost completely determined. The family of GSR curves obtained in this fashion directly or indirectly supplies information about such conventional measures as the display's spot size, bandwidth, luminance capability, dynamic range (gray shades or dB), resolution, contrast, etc. as shown in Figure 28.

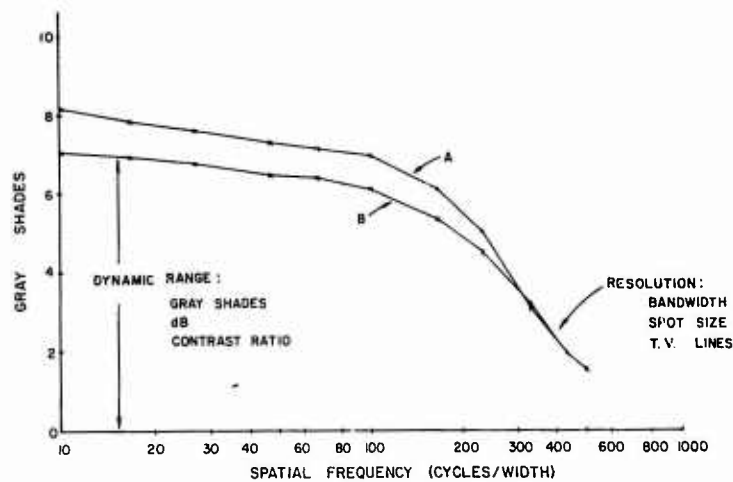


Figure 28. GSR Curves for the Ferranti Miniature CRT Display with Peak Luminance Levels of A) 50 footlamberts and B) 600 footlamberts

UNITARY METRICS OF DISPLAY QUALITY: MTFA CONCEPT

Snyder (17) has proposed that the area under the MTF curve be used as a measure of television display quality. This concept, referred to as the modulation transfer function area (MTFA), was originally introduced in 1965 as a unitary measure of photographic image quality. The MTFA makes use of the MTF of the imaging system, thereby retaining the analytic convenience of component analysis. In addition, the MTFA accounts for other variables critical to the perception of the displayed information. Figure 29 shows the MTFA as the area bounded by the MTF of the display system and the visual demand curve (7). The visual demand curve is derived from psychological data relating to the threshold performance of the human visual system for sine wave patterns. The point on the graph where the visual demand curve intersects the MTF curve is the limiting resolution of the display. Beyond this frequency, the modulation contrast is insufficient for the average human observer to resolve the spatial pattern; therefore, the area under the MTF curve beyond this point does not impact operator performance since it is not visible to the operator.

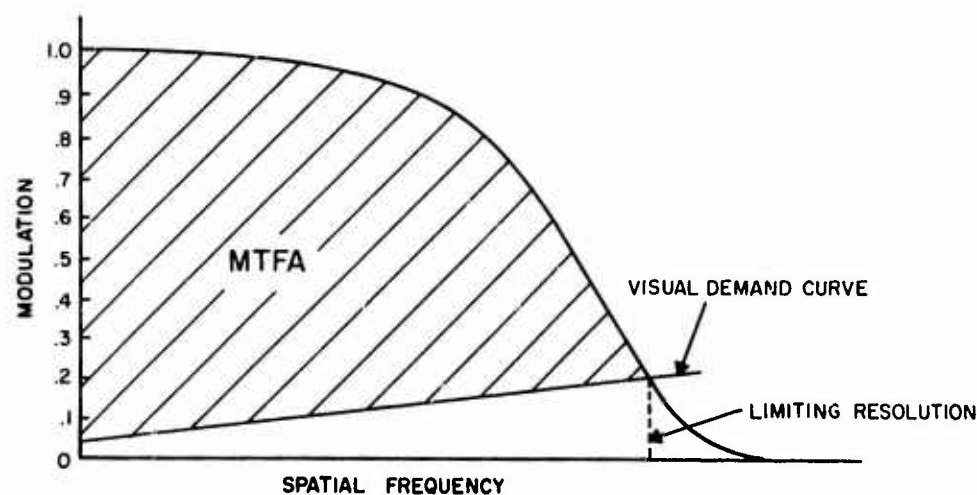


Figure 29. MTFA Concept as a Display Quality Metric. The area between the visual demand curve and the MTF of the display has been shown to be a good correlate of observer performance.

The same rationale can be used to justify the plausibility of using the area under the SWR curve instead of the MTF curve as a measure of television image quality. The lower curve, the visual demand curve, will remain unchanged. The intersection of the SWR curve and the visual demand curve will retain its importance as the value of limiting resolution.

An obvious difficulty arises conceptually when using an area measure since the implication is made that the area between the SWR or MTF curve and the visual demand curve is isotropic; that is, any element of area under the curve is of equal importance with all other area elements of equal size. This condition does not exist in the case of MTFA. This is due to the fact that modulation contrast is a nonlinear parameter with respect to the human visual system. As previously described, however, the GSR was specifically derived to linearize the CRT response curve with respect to human vision. It is therefore reasonable to assume that a better measure of operator performance is the area between the Gray Shade Response Curve and the human visual demand (or threshold) curve, as shown in Figure 30. This area is referred to as the Gray-Shade-Frequency product, or GFP.

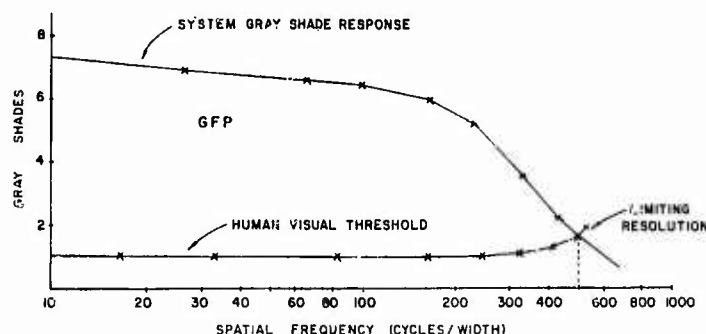


Figure 30. The Unitary Quality Measure Designed GFP

Theoretically, the GFP should provide a better measure of display quality, as it relates to operator performance, than the MTFA. However, both measures rely on the so-called human visual demand curve to define the lower bounds of the area function, thus emphasizing the importance of this curve. The conditions under which this function is obtained can vary its shape and position considerably. To obtain the best results, this curve should be obtained under conditions similar to those encountered with the display. Such parameters as color of the display, one-eye versus two-eye viewing, signal/noise ratio, total field-of-view, average luminance, eye adaptation level and many others must be considered when obtaining or employing the visual demand curve for use with the unitary area metrics.

As an initial effort to compare operator performance with various unitary metrics, a small pilot study was initiated. The next section of this report describes the unitary measures tested, the operator task and the results of the experiment.

RESULTS OF A PILOT STUDY

From the preceding discussion, four unitary metrics can be constructed. These are:

$$\begin{aligned}\bullet \text{ MTFA LINEAR}^* &= \int_0^L (\text{MODULATION}) d(\text{FREQUENCY}) \\ \bullet \text{ MTFA LOG}^* &= \int_f^L (\text{MODULATION}) d(\text{LOG FREQUENCY}) \\ \bullet \text{ GFP LINEAR} &= \int_0^L (\text{GRAY SHADES}) d(\text{FREQUENCY}) \\ \bullet \text{ GFP LOG} &= \int_f^L (\text{GRAY SHADES}) d(\text{LOG FREQUENCY})\end{aligned}$$

where L = limiting resolution

*Note: The MTFA linear/log can be further refined to a sine wave response area measure, i.e., SWRA log/linear.

For each case, the area under the human visual demand curve (in compatible units) is subtracted out to find the net value of each of the four metrics. The pilot study was designed to determine which of these four metrics best correlates with operator performance.

Subjects

All subjects for this study were university students between 18 and 23 years old with 20/20 vision or vision corrected to 20/20.

Task

Subjects were required to perform a target recognition task using five vehicle type targets. Targets were viewed monocularly on the face of a Ferranti Type 02B/97D2 CRT display (built by Honeywell, Inc. for helmet-mounted display applications) through a high quality magnifying eyepiece. The apparent display size was 10.0° high by 13.3° wide. At the start of a trial the target appeared as a small object in the center of the screen. The target increased in size until the subject was able to recognize the target. The subtended angle of the diagonal dimension of the target at recognition was recorded as the measure of operator performance.

Equipment

Figure 31 shows a block diagram of the equipment used for this study. The Experimenter's Station is shown in Figure 32 and the subject's station in Figure 33.

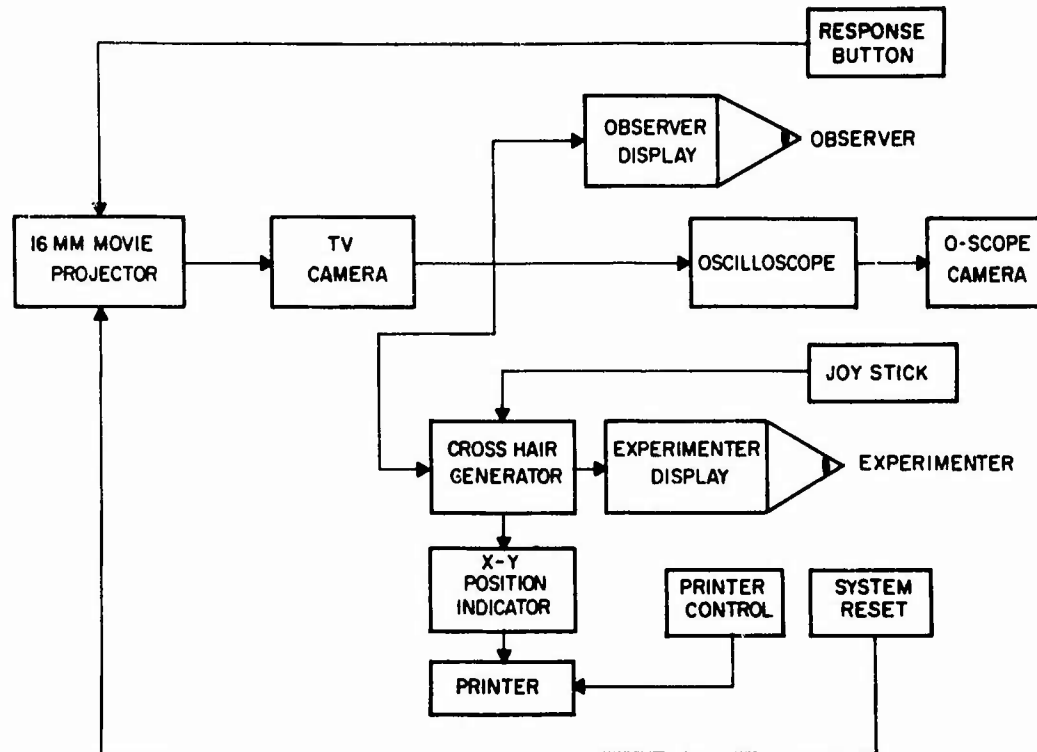


Figure 31. Block Diagram of Equipment

The stimulus material was prerecorded on black and white 16mm movie film. These films were made by slowly zooming in on 8 in. by 10 in. photographs of the target vehicles. The target increased from its initial size to 10 times that size in approximately 20 seconds. The 16mm movie camera was trained on the picture for about two seconds before the zoom motion began, thus giving the subjects time to fixate on the target. Each of the five targets was photographed in four orientations giving 20 different target runs.

The experimenter's station converted the 16mm movie to 525 line rate video by projecting the film onto the surface of a high quality Cohu 2810 TV camera. The video was displayed on both the experimenter's monitor (shown in Figure 32) and the subjects' miniature CRT display. At the time of recognition the subject pressed a button which blanked the video signal to

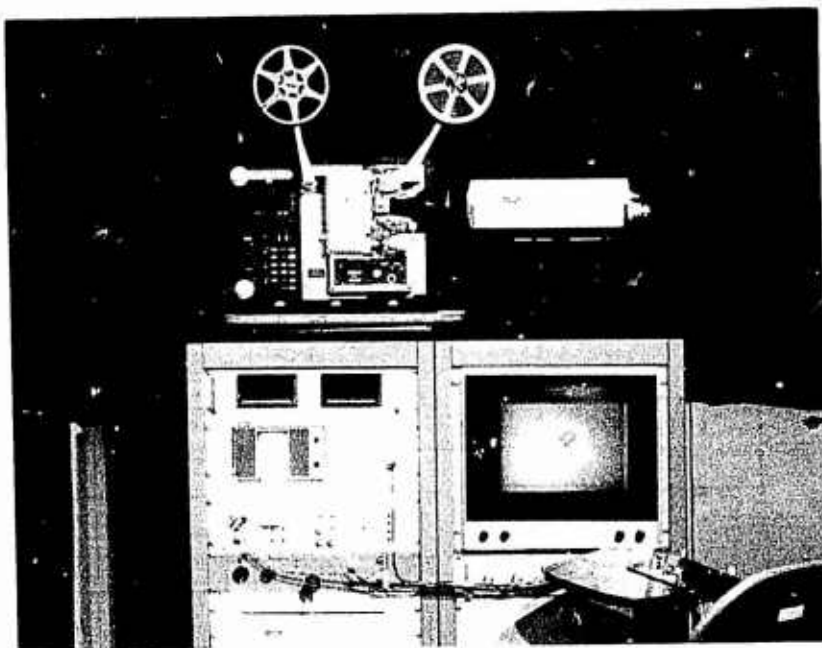


Figure 32. Experimenter's Station



Figure 33. Subject's Station

his display. The experimenter then determined the diagonal size of the target with the aid of an electronic crosshair and control joystick. The resulting X-Y coordinates of the two points defining the ends of the diagonal size were then printed out by a Digitec Model 6130 digital printer

All photometric measurements were made using a Gamma Scientific Co. Model 2400 microphotometer and a specially designed Systems Research Laboratories, Inc. video sine wave test signal generator.

Calibration

Display quality was adjusted by changing the spot size of the CRT. Three different spot sizes were used resulting in the three different SWR curves shown in Figure 34.

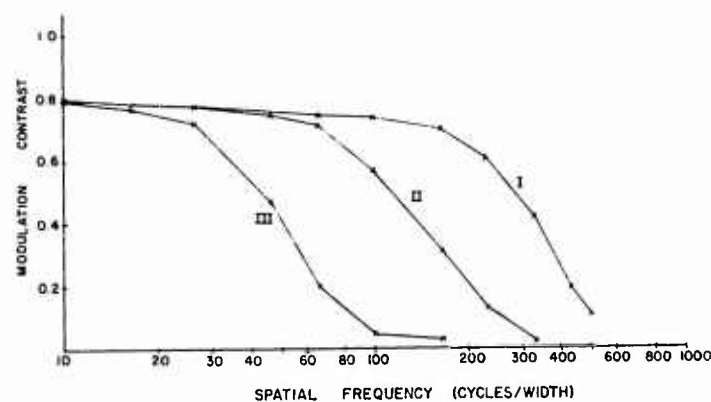


Figure 34. Three Display SWR Curves for the Three Spot Sizes Used

The display and TV camera were tested for stability to ensure that the signal levels would not drift as a function of time.

It was found that the CRT display stabilized after a few minutes but the TV camera required two hours warm-up time before it stabilized. The SWR and the VTF of the display were measured every morning after warm-up, before running subjects and every evening immediately after subject testing to verify that the equipment had not drifted. Polaroid pictures of the oscilloscope showing the TV camera video signal were taken before and after each subject run to ensure that the camera signal levels remained constant.

Since the camera MTF was part of the full video system being used in the study, it was necessary to modify the SWR curves to reflect the degradation due to the TV camera. All other components of the system had a negligible effect on image quality compared to the TV camera and the CRT display.

The amplitude response of the TV camera was measured and normalized to unity at 18 cycles/display width (see Figure 35). This curve was then multiplied, point by point, with the SWR curve, to obtain the SWR curves of the total video system for each display condition. Figure 36 shows the resulting SWR curves for the system and Figure 37 shows the same curves transformed to GSR curves.

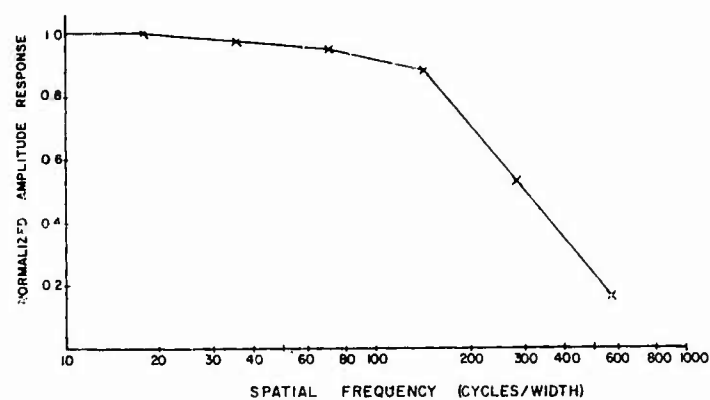


Figure 35. Amplitude Response of TV Camera

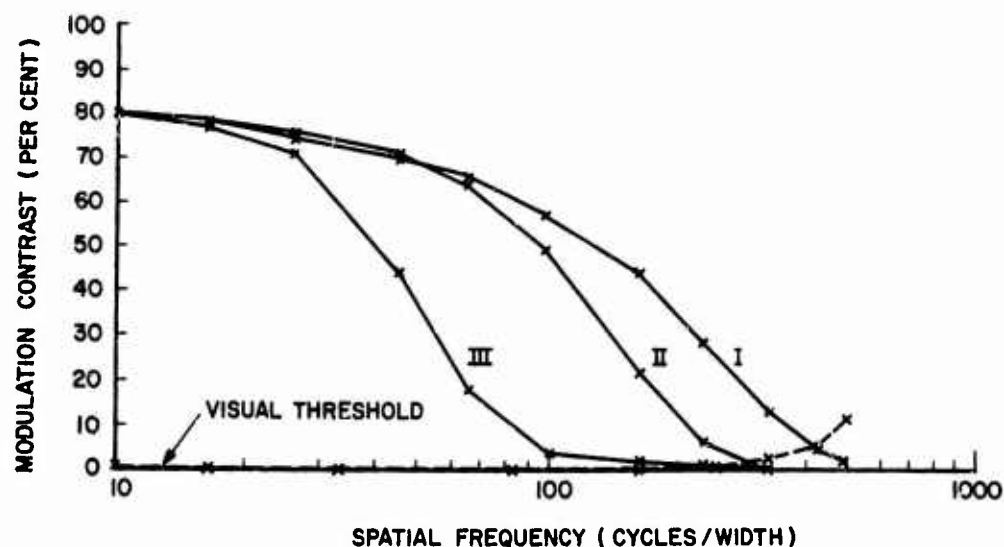


Figure 36. Total System SWR Curves for the Three Spot Sizes
13.3° Display Viewing Width

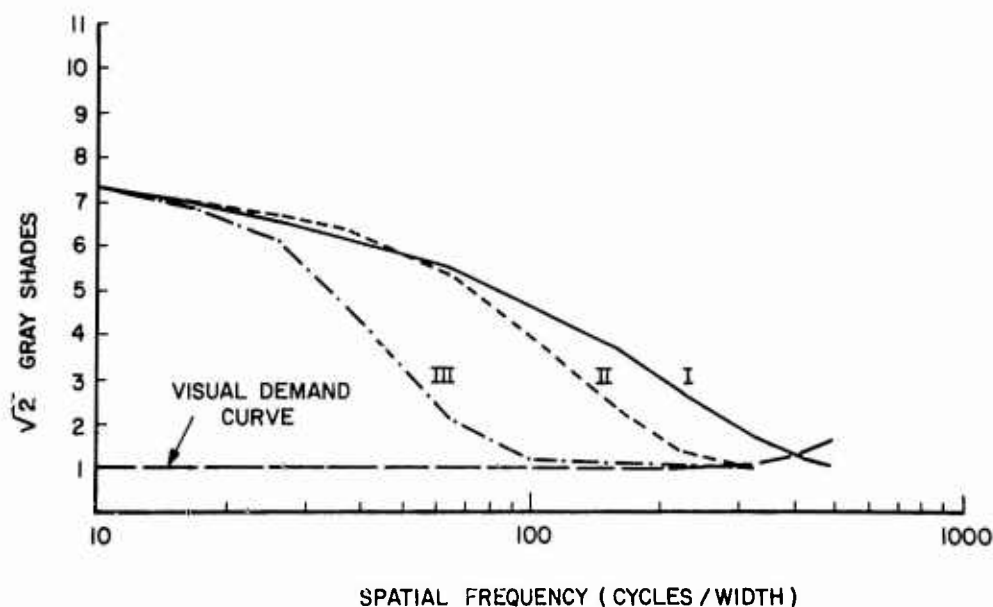


Figure 37. System GSR Curves for the Three Spot Sizes

The human visual threshold curves shown in Figures 36 and 37 were obtained by Davidson (reference 7) and transformed into units compatible with the SWR and GSR graphs.

On the experimenter's station, the X-Y electronic cross hair was calibrated each morning after equipment warm-up.

Procedure

Each subject's visual acuity was measured immediately prior to testing. After it was ascertained that the subject had 20/20 vision or vision corrected to 20/20, he was seated at the subject's station. Instructions were provided both verbally and in writing. Pictures and models of the five vehicle targets were studied by the subject until he was able to easily identify each by name. The subject was then given a practice run on the first target to further familiarize him with the procedure. (This target and target orientation was also used for data collection purposes on run number 21.)

The subject viewed the display through either his left eye or right eye at his option. The target initially appeared as a small object in the center of the display and then slowly increased in size until it subtended an angle of approximately 6-1/2°. In all cases the subject was unable to identify the target at the onset but was able to identify it before it reached full size. Subjects were instructed to identify the target when they were "virtually certain" that they knew what it was. This instruction was designed to minimize guessing, yet still provide motivation for identifying the target early in the run.

The subject pushed a button when he thought he could identify the target. This stopped the motion picture projector and blanked the video to the subject's display. The subject's response was recorded by the experimenter and the subtended angle of the target was measured from the experimenter's station with the aid of the X-Y electronic cross hairs and digital printer. The motion picture projector was then turned on, the subject's display was again activated and the subject was permitted to view the remaining portion of the run. This gave the subject relatively rapid feedback as to the correctness of his response.

Eight subjects were used for each of the three display configurations. Each subject was run only once.

Results and Discussion

Table 2 gives a summary of performance data for the three display conditions tested.

TABLE 2. SUBJECT PERFORMANCE DATA

Display Condition	1	2	3
Mean Subtend Angle of Target at Recognition	1.29°	1.42°	2.33°
Standard Deviation	.36°	.26°	.14°

The four unitary metrics under consideration were calculated from the full system SWR curves shown previously in Figure 36. The resulting calculated unitary metric values for each display condition are shown in Table 3.

TABLE 3. THE FOUR UNITARY METRICS FOR THE THREE DISPLAY CONDITIONS

Display Condition	Metric			
	SWRA Linear*	SWRA Log*	GFP Linear	GFP Log
1	140.4	.911	922	6.49
2	92.8	.807	625	6.22
3	36.1	.534	263	3.96

*Note: SWR was used instead of MTF since it has already been shown that the SWR is a more accurate description of display capability than is the calculated MTF.

The data from Tables 2 and 3 are shown in graphic form in Figures 38 through 41. It is apparent from these graphs that all the area measures correlate with subject performance to some degree. Of the four metrics, the GFP Log and MTFA Log show the most linear relationship with subject performance. Since there were only three display conditions, yielding only three points to define a line, it is difficult to state with any degree of certainty that the GFP Log is a better correlate of subject performance than the MTFA Log. However, from the results of this study, it is possible to state that the GFP Log metric is at least as good as the MTFA Log as a measure of usable display quality, and does relate to subject performance. More definitive validation studies of the GFP Log metric are planned for the near future.

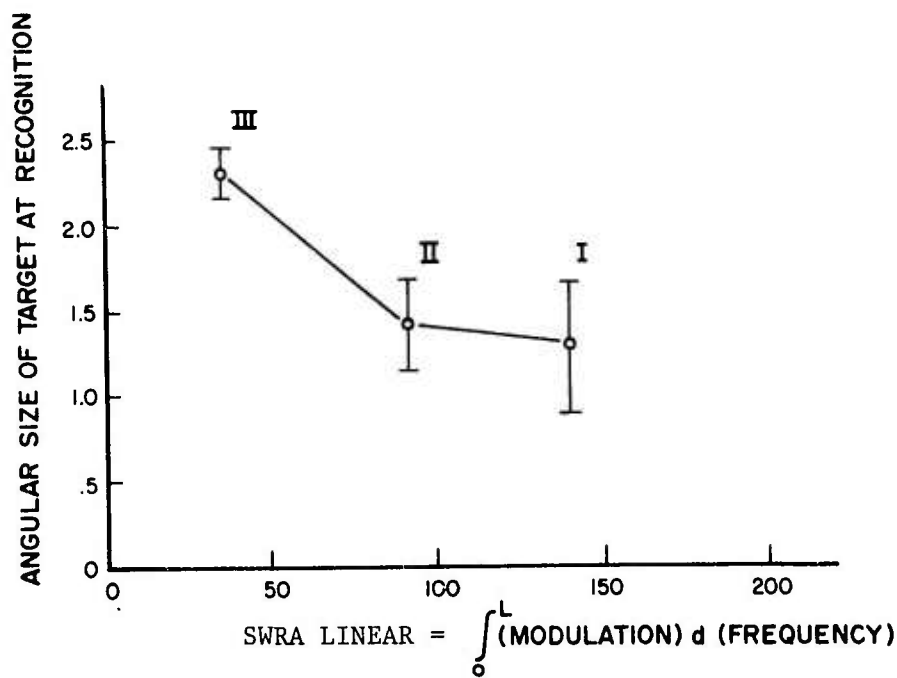


Figure 38. Performance versus SWRA Linear

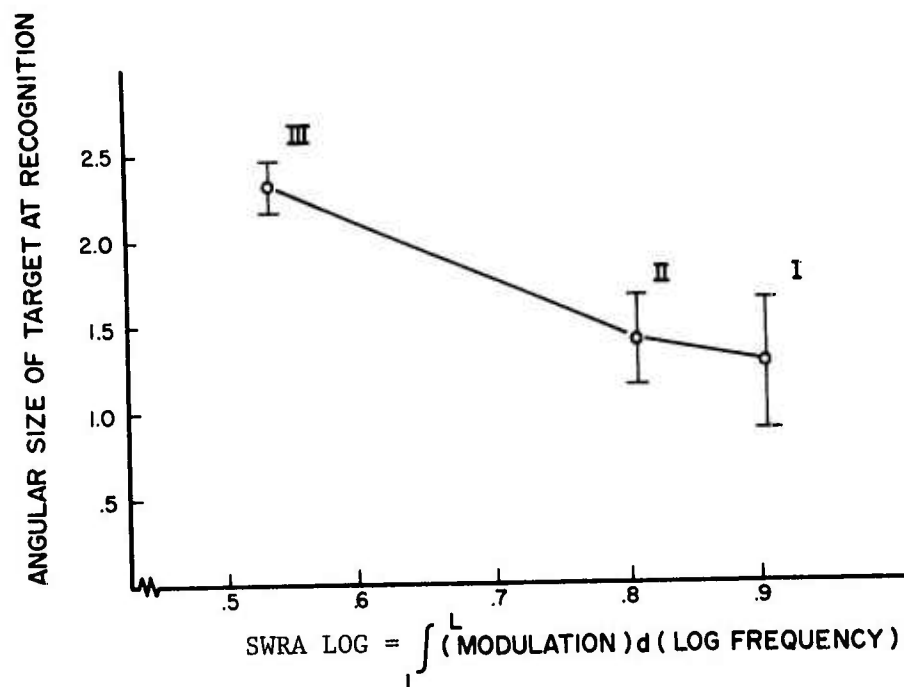


Figure 39. Performance versus SWRA Log

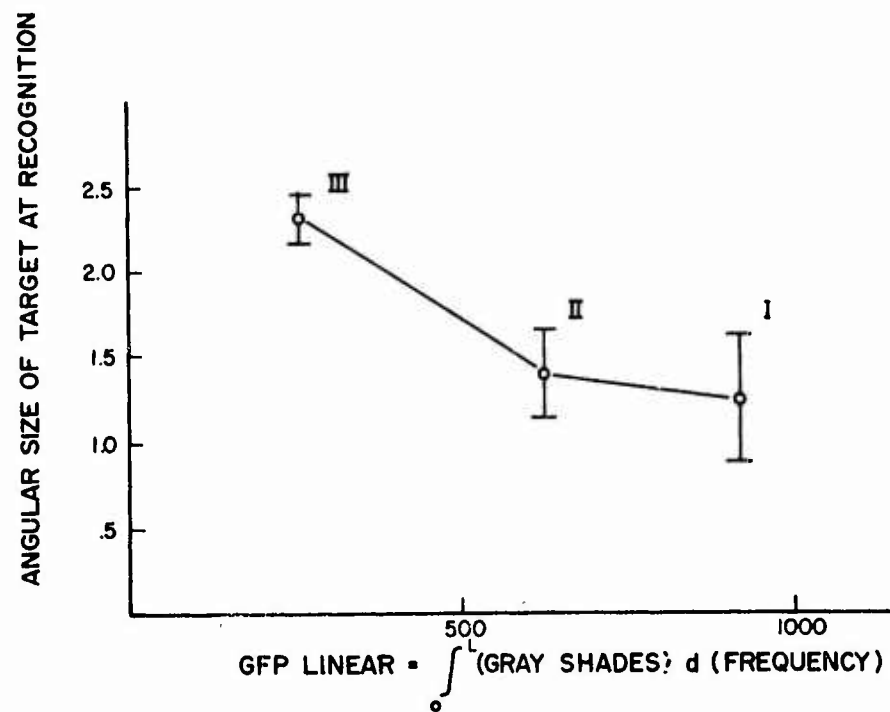


Figure 40. Performance versus GFP Linear

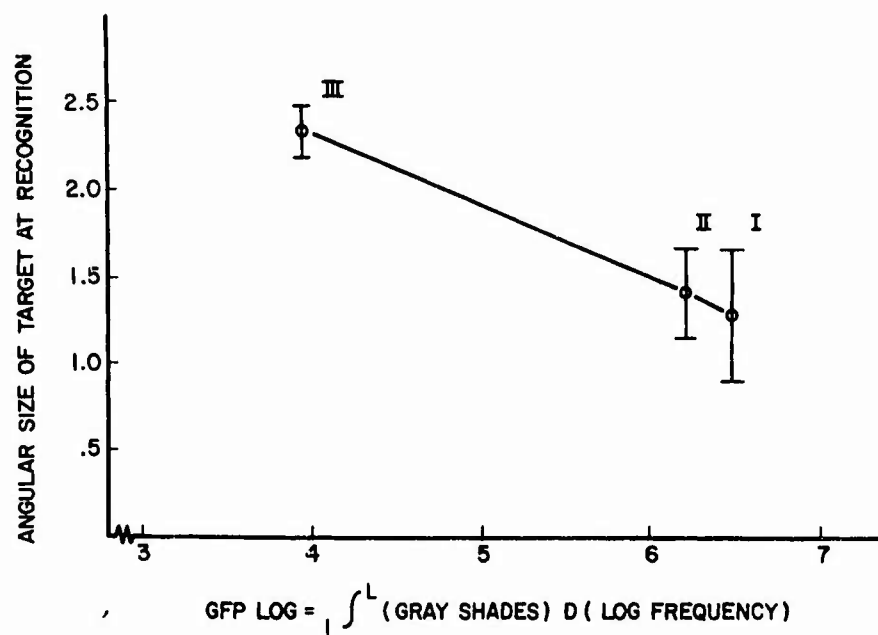


Figure 41. Performance versus GFP Log

CONCLUSIONS AND RECOMMENDATIONS

The Sine Wave Response (SWR) measurement technique described in this report has been proven to be valuable for comparing the display quality of television type CRT displays. Since it directly measures the actual contrast modulation available on a CRT display as a function of spatial frequency, it provides more accurate information on the quality of the display than does the MTF.

To date, hundreds of VTF and SWR measurements have been made on more than a dozen different miniature and large size CRT displays. SWR and VTF data on the miniature CRT's have resulted in improved miniature CRT displays for helmet-mounted displays. The SWR and VTF have also been used as tools to calibrate and properly adjust CRT display conditions for various human factors and operator performance studies.

The Gray Shade Response (GSR) curve derived from the SWR is probably the best overall method of defining a display's capability. This curve directly or indirectly contains almost all of the current conventional indicators of display performance such as spot size, luminance, resolution, dynamic range, gray shades, contrast ratio, etc.

The Gray-Shade Frequency Product (GFP) derived from the GSR and the human visual threshold curve (visual demand curve) seems to be the most promising predictor of subject performance for a target recognition task. Theoretically, since both dimensions of the area measure are linear with respect to human vision, the GFP Log should correlate highly with display-observer information transfer, and thus subject performance.

There are several areas requiring further study. First, the validity of the GFP Log as a predictor of subject performance must be investigated in more depth. Since the GFP can be affected by bandwidth, spot size, ambient illumination, light scatter and other variables, it is necessary to determine if operator performance is affected to the same degree as the GFP. A study of this nature is currently being planned and should be in progress soon.

The GFP is also affected by the human visual demand curve. It is therefore necessary to ensure that the visual demand curve is "correct" for the particular display situation. For example, the demand curve changes as a function of color and as a function of one-eye or two-eye viewing. The visual demand curve needs to be measured for each of these situations.

Another area of consideration is the use of $\sqrt{2}$ luminance ratio to define a gray shade. It is probably necessary to change this "engineering" definition of gray shade depending on the display color and viewing condition. A red display, being more difficult to see, might have fewer discernible gray shades than a green display having the same SWR curve. Basic psychophysical research needs to be performed in this area in such a way as to be applicable to the GFP Log model.

Other variables that may affect this visual threshold curve are signal-to-noise ratio of the video, total viewing area, and eye adaptation and accommodation level. All these have a place in the GFP Log model but the basic research has not yet been accomplished.

It should be noted that the SWR measurement is made in one dimension only, even though the display quality definition problem is two-dimensional. The effect of the number of scan lines of a display on the SWR and GFP Log metrics has not yet been investigated. It is the opinion of the authors that the best measure of vertical resolution or quality of a display is simply the number of scan lines. It should be possible to incorporate this aspect of line scan displays into the GFP Log model to obtain an overall two-dimensional quality metric. Investigations in these areas are planned for the future.

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